

## Proliferation Networks in Theory and Practice

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### Introduction

The discovery of the A.Q. Khan proliferation network has sparked inquiry into the roles of clandestine transactions in the spread of nuclear, chemical, and biological weapons and their delivery systems.<sup>[1]</sup> Although the scale of Khan's operation is perhaps greater than that of previous networks, such networks (clandestine or not) are hardly new or unique. However, in order to begin to answer these questions, the mechanisms that guide the formation and dissolution of networks must be better understood.<sup>[2]</sup>

Is the A.Q. Khan network unique among clandestine proliferation networks? How easily can it be fragmented, taken apart, and shut down? Will it regenerate or be reproduced by parallel networks? Despite the impressive scale of Khan's operation, its structure as a proliferation network is not unique. Very little has been written about why proliferation networks look the way they do. Like the demand-side question of why states seek weapons, the supply-side question of where states try to get needed materials from is significantly affected by efforts of powerful actors to limit access to nuclear technologies. Assessing these efforts, however, requires some knowledge of the structure of proliferation networks. Without taking this into account, efforts to limit network structures can be useless, or even counterproductive, if shutting down one supplier only results in others taking its place. This article incorporates theories from transaction-cost economics and network analysis to explain the general structure of proliferation transactions as markets, networks, or hierarchies. It also explores theories as to why particular network ties are formed—whether due to similar structural positions, similarity of attributes, or pre-existing ties. After looking at a few proliferation structures to see which mechanisms seem to dominate transactions, it concludes by briefly outlining some policy implications.

### Markets, Networks, and Hierarchies

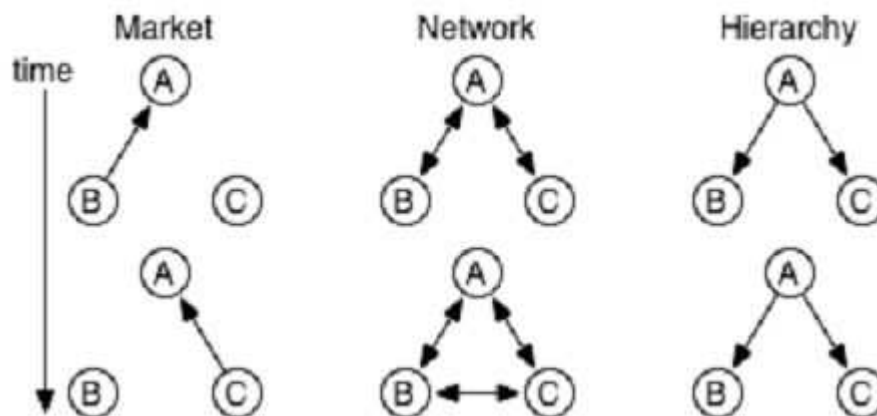
Economists and sociologists have identified three basic structures through which transactions occur: markets, networks, and hierarchies.<sup>[3]</sup> In a market model of transactions, goods are exchanged between actors who have no past and no future connections. Each transaction is autonomous, and communication occurs through price. In the hierarchical model, a single actor determines what transactions occur with subordinate actors. Transactions are determined

through power. In a network model, transactions occur between actors that have a longer-term, repeated relationship. Reciprocity norms and reputation concerns help to govern transactions.

Suppose that you'd like a cup of coffee. In a market, each time that you desire a cup, you determine which of several suppliers has the lowest price with the quality of product you desire. You buy it there. In a hierarchy, you go out and buy a coffee maker and make it yourself instead of outsourcing coffee production to an external supplier. In a network, you develop a relationship with a particular coffee place over time. A barista may have particular knowledge of the type of coffee that you like or may know a method of making coffee that is superior to that at other places. In proliferation networks, the question is whether a particular part or system is bought on a market, through a relationship with a particular supplier or set of suppliers, or whether a proliferator chooses to produce parts or systems in-house.

All three structures are actually networks. In [Figure 1](#), A has demand for a product that may be supplied by B and/or C. In a market network, transactions between two or more nodes are asymmetrical. There is no stable connection between different actors over time, so A may transact with B one time and with C another. In the more stable, hierarchical models, a superior A orders inferior(s) B and/or C to produce the product. In a network transaction, there is a more symmetrical and stable relationship among actors. A not only exchanges products with B and C, but also forms a relationship with each that is repeated over time. In a network, relationships may also grow and increase over time between previously disconnected agents, e.g., B and C.[\[4\]](#)

**Figure 1: Market, Network, and Hierarchy Relationships**



*Market transactions are asymmetrical and change over time. Network transactions are more symmetrical and are repeated. Hierarchical transactions are top-down and stable.*

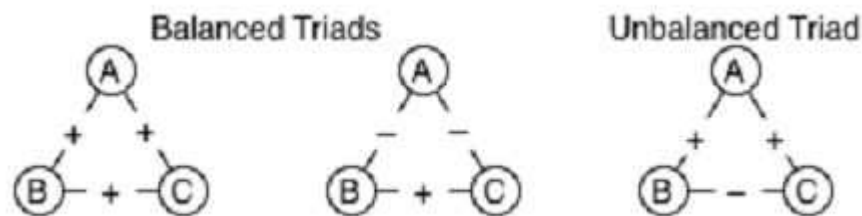
Transaction-cost economics first distinguished the conditions under which markets and hierarchies were likely to form. Market-type transactions occur when transaction costs are low, exchanges are straightforward, knowledge is symmetrical, and repetition is unnecessary. Hierarchies arise when opportunism is high and rationality is bounded such that contracting for all contingencies is difficult.[\[5\]](#) The network form of transaction was subsequently identified by other scholars as a distinct category (as opposed to a mixing of ideal types) that relies upon reciprocity and collaboration to govern transactions. This form is particularly well suited to the transmission of knowledge. Knowledge is less constrained in a network than it is in a market or hierarchy. Market incentives treat knowledge as a commodity to be sold rather than given, while hierarchies constrain the conduits through which knowledge might pass.[\[6\]](#) Knowing which of these forms—

or what combination of these forms—proliferation networks are likely to take is crucial in evaluating efforts to stop them.

The question remains, however, as to why relations form between some potential partners in a network and not others. Unfortunately, scholars have not elucidated particular conditions under which network transactions will take place instead of hierarchies or markets or why particular network ties are favored within repeated relational transactions. Network analysis does specify some general mechanisms through which new ties are likely to be created. These generally fall into one of two categories: relational mechanisms or individual mechanisms. Relational mechanisms specify how the relative locations of two actors within existing networks influence the likelihood of ties occurring, while individual mechanisms specify how particular attributes of individual actors make pairs of actors more or less likely to form ties.

Two of the most prominent positional mechanisms in network analysis are structural balance and structural equivalence. Structural balance hypothesizes that between three actors, only certain patterns of positive (affect) and negative (enmity) ties can exist.[7] Specifically, given any three actors, positive or negative ties between the three must be conserved. Essentially, the friend of my friend is my friend, and the enemy of my enemy is my friend. [Figure 2](#) demonstrates three triads. In the left and middle triads, no role strain exists, since all relations are compatible. The right triad is unbalanced. Role strain will occur, and over the longer term such a triad is unlikely to be found.

**Figure 2: Balanced and Unbalanced Triads**



*The left and center triads are balanced due to transitivity. The right one violates transitivity—if A likes B, and A likes C, then B should like C, etc—and is unbalanced.*

Structural equivalence hypothesizes that actors in similar structural positions vis-a-vis each other will act in similar ways. In particular, they may be more likely to form ties, although in some circumstances, they may compete if there is conflict over scarce resources. Two actors are structurally equivalent if they share the same ties with the same actors.[8] In the middle network pictured in [Figure 1](#), B and C are structurally equivalent and form a connection over time. Structural equivalence is a slight misnomer, since it measures equivalence with respect to particular actors rather than referring to the type of relationship.[9]

Since exact equivalence is rare in social data, positional analysis attempts to identify actors who are structurally similar. By virtue of their positions and similar structural pressures to conform to particular roles, these actors are likely to act in similar ways. To take a specific role as an example, students are likely to act in similar ways, whereas students and teachers, by virtue of their different positions, act differently. In particular, students are more likely to form ties between each other rather than with the teacher. Because of their similar positions, they are likely to see each other as members of the same group. In-group favoritism is a well-established phenomenon in social psychological studies.[10] Such groups can also become subdivided into smaller ones. Identifying salient groups requires in-depth knowledge of the groups in question.

Individual mechanisms tend to be related to the broad notion of homophily,<sup>[11]</sup> or the tendency of actors who are similar in certain ways to form ties based on their common attributes. So states with similar attributes—common ideology, for example—may be more likely to form ties with each other. The same attributes that bring them together, however, may also promote competition in certain cases. On the other hand, states with complementary attributes may be more likely to form ties with each other.

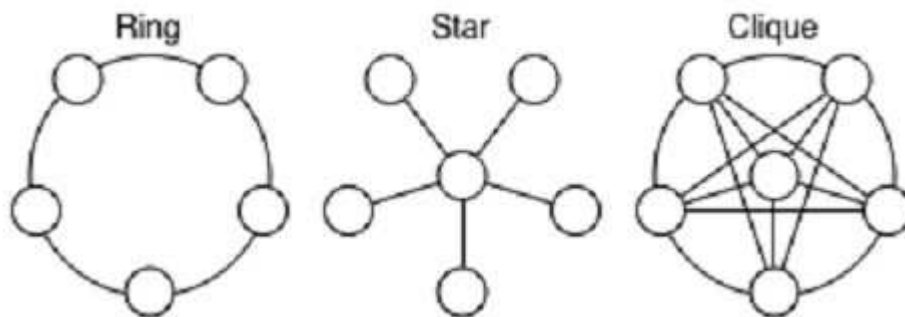
Finally, the types of pre-existing network connections also affect the creation of new network ties. States that already have extensive ties are more likely to be linked in proliferation networks, especially if these ties are military and/or clandestine in nature.

## Network Structures

Networks can take on a variety of structures. The efficacy of policies for limiting the supply of nuclear technologies against a given node in a network, or for the network as a whole, depends on the overall structure of the network. While analysis of supply networks is ultimately a function of all ties within that network, three archetypes can be loosely defined.

Networks can be structured: as rings or circles in which the connections between nodes form a circle; as a star in which every node is connected through a central hub; or as a clique, a much denser network in which each node is directly connected to every other node. See [Figure 3](#). The figure also illustrates the vulnerability of each type of network, determined, in part, by the number of cutpoints or cutsets it contains. A cutpoint is a node without which the network would break into one or more pieces.<sup>[12]</sup> A cutset is a set of nodes in a network that similarly is vital to the network. Therefore, a ring is a network in which each node is directly connected to only two neighbors. The network is connected and has no cutpoint. However, any two non-adjacent nodes constitute a cutset, so a ring is still somewhat vulnerable. A star is a network that has a single cutpoint that isolates all nodes. It is, however, robust to attacks on nodes other than the central hub. An  $n$ -clique (in [Figure 3](#), a 1-clique) is a network or sub-network in which every node is connected to every other node through  $n$  ties. It is the most vulnerable to attacks.<sup>[13]</sup>

**Figure 3: Simple Network Structures**



*Simple network structures.*

[Figure 3](#) shows that if the structure is a ring or a clique, then there is no single node (state) that could be shut down to unravel the entire network; consequently, actions against single nodes are likely to be ineffective. Actions against more than one node, however, can isolate parts of the circle network. For a clique, global options—i.e. those that affect all nodes—might seem best. Densely connected, clique-like networks are highly decentralized—no single state holds a crucial

position in the network. In one sense, decentralized networks are easier to shut down in that connections to additional nodes in the network are easier to discover. On the other hand, a star network—i.e. a hub-and-spoke pattern—is highly centralized, and efforts are best concentrated on eliminating the central node and preventing other nodes from becoming hubs.

## Knowledge and Networks

Networks may be limited by other factors, such as availability of particular technologies and whether they require special knowledge in order to build and/or operate them. Such factors also affect the structure of transactions. Both production of fissile materials and the design and construction of nuclear weapons require a great deal of tacit knowledge.

Tacit or “shop-floor” knowledge is that which cannot be formulated in words or symbols, but must be learned through trial-and-error processes. Bicycle riding is a well-known example of tacit knowledge. It is impossible to learn how to ride a bicycle simply by reading an instruction manual. Nuclear weapons design and production are both heavily dependent on tacit knowledge. Even if a state possesses a bomb design, many additional steps are required for both fissile materials production and weapons design in order to develop a nuclear weapons arsenal. Both Britain and the Soviet Union began by attempting to replicate a U.S. design that they possessed, yet both had to undertake major efforts in order to effectively produce their arsenals. Every subsequent nuclear program has taken longer than the original Manhattan project to build an initial nuclear weapon, despite transfer of information and even scientists from one program to another.<sup>[14]</sup> After the initial step of building an implosion weapon, however, some states have been quicker to develop two-stage weapons. One of the major preoccupations of the U.S. nuclear weapons complex is attempting to retain such knowledge in the absence of testing.<sup>[15]</sup> Ballistic missile development—while also requiring tacit knowledge—seems to be less restricted because missile design and testing are more easily divided into discrete elements.<sup>[16]</sup>

What is it about a nuclear weapon that requires tacit knowledge? Being able to cast the weapon’s fissile materials and high explosives into the proper shapes is a difficult task that requires direct experience that cannot be simply extrapolated from other industrial processes.<sup>[17]</sup> Siegfried S. Hecker, former director of the Los Alamos National Laboratory, noted that, “The real secrets are in the details of the metallurgy, the manufacturing and the engineering.”<sup>[18]</sup> Tacit knowledge consequently plays a major role in structuring proliferation transactions. The high knowledge requirement of nuclear weapons production makes transactions more likely to be hierarchies rather than networks, and networks rather than markets. Nuclear weapons projects operated as hierarchies, however, are likely to be more costly. Acquisition of the requisite knowledge requires extensive internal research and development. The Manhattan project, for example, cost \$21 billion in 1996 dollars,<sup>[19]</sup> or about \$5 billion per weapon initially produced. It employed tens of thousands of engineers as well as scientists. In short, a nuclear weapons program is not only a technical feat, but also an organizational one.

## Proliferation Networks in Practice

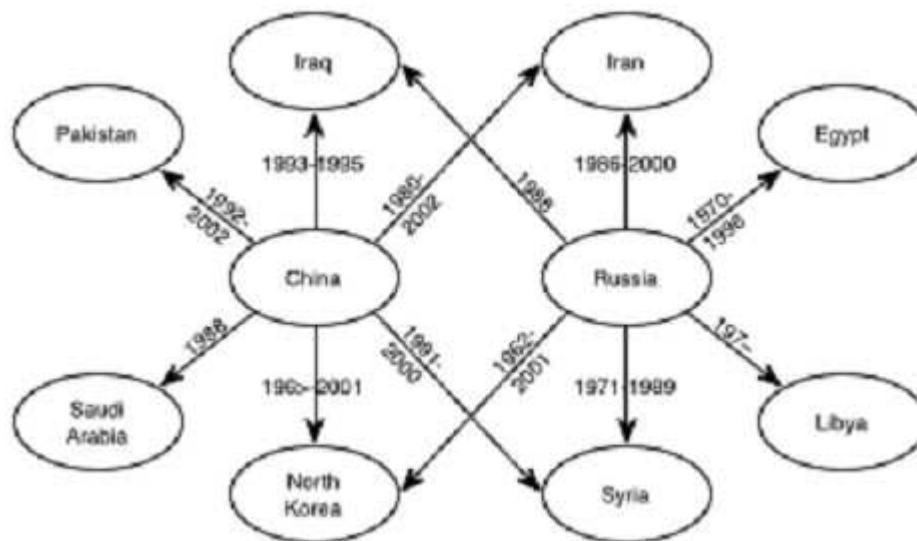
Nuclear proliferation transactions between states—whether intentional or not—are as old as nuclear weapons. British scientists from the Manhattan project carried knowledge about nuclear technology back to the United Kingdom, while Soviet spies managed to extract documentation of U.S. efforts. Full-blown networks, in which transactions occur among more than two isolated participants, are a more recent development. Many transactions are clandestine, and so any diagrams describing the structure of these networks are necessarily uncertain and potentially incomplete.

The best-documented proliferation networks involve the transfer of ballistic missile technology and are summarized in [Figures 4](#) and [5](#). Missile proliferation data in these figures comes from the

Nuclear Threat Initiative and extends through 2002.[20] Unique and/or minor incidents were discarded. Year ranges do not indicate constant assistance, but rather the first and last years during which known transactions occurred. Ranges ending in 2000 or later may represent ongoing relationships, while ranges that end before 2000 more likely indicate terminated relationships.

The first-tier missile proliferation network is pictured in [Figure 4](#). It does not include all known transactions—and, of course, cannot include unknown ones. However, it is clear that first-tier proliferation has been dominated by Russia and China, each having shared technology with four states—North Korea, Syria, Iran, and Iraq. Additionally, Russia has assisted Egypt and Libya, while China has assisted Pakistan and Saudi Arabia. First-tier missile technology transactions are market-like. There are multiple suppliers, transactions are one-way, and reciprocal knowledge-sharing or trading does not occur. The structure of transactions resembles a star network with two hubs. Transactions with the four states that purchased missile technology from both China and Russia do not shed any light on why particular ties formed beyond market mechanisms. On the other hand, Pakistan, Egypt, Saudi Arabia, and perhaps Libya, acquired technology from only one of the two hubs, likely due to existing security ties. In the case of China and Pakistan, both faced a similar threat: India. The ties between Russia and Egypt and Russia and Libya may have more to do with broader Cold War strategies. The China–Saudi Arabia connection is harder to explain. And, China may have also provided assistance to Libya, as well.

**Figure 4: Network Structure of First-Tier Ballistic Missile Proliferation**



*Nodes are placed for clarity. Minor nodes are excluded.*

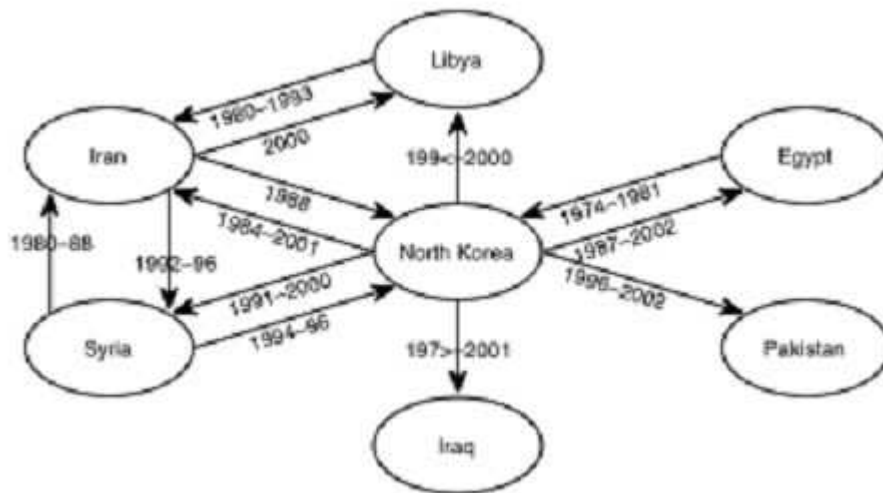
Since joining the Missile Technology Control Regime (MTCR) in 1995, Russia has decreased its proliferation of missile technology—although it is still suspected of assisting North Korea and Iran, albeit at a lower level. China likewise has agreed to abide by the MTCR. In 2000, it pledged not to assist in the development of nuclear-capable missiles and issued related regulations in 2002. However, it was still assisting Pakistan and Iran at that point.[21]

The second-tier ballistic missile proliferation network is depicted in [Figure 5](#). Only the core, second-tier proliferators are in this diagram. Other countries that received only limited assistance—e.g., Yemen, Sudan—are excluded. All members of this network are also members of the first-tier network. Unlike the first-tier transactions, these transactions resemble a clique



structure, and relationships are more reciprocal. However, with the exception of Iran and North Korea, no two proliferators are connected to each other through missile trades. North Korea forms the center of this missile proliferation network, delivering missile technology to Egypt, Iraq, Libya, Syria, Pakistan, and Iran, among others. Iran forms a smaller hub for missile sales, linking North Korea, Syria, and Libya. Unlike the first-tier, formation of these networks seems to uphold transitivity and structural equivalence; where relationships have lasted for a significant period of time between one of the earlier hubs (China or Russia), new ties have formed. Three of the four core missile proliferators who received technology from both China and Russia later developed links between each other (Syria, Iran, and North Korea), although the Syria–Iran link developed before they were connected through Russia.

**Figure 5: Network Structure of Second-Tier Ballistic Missile Proliferation**

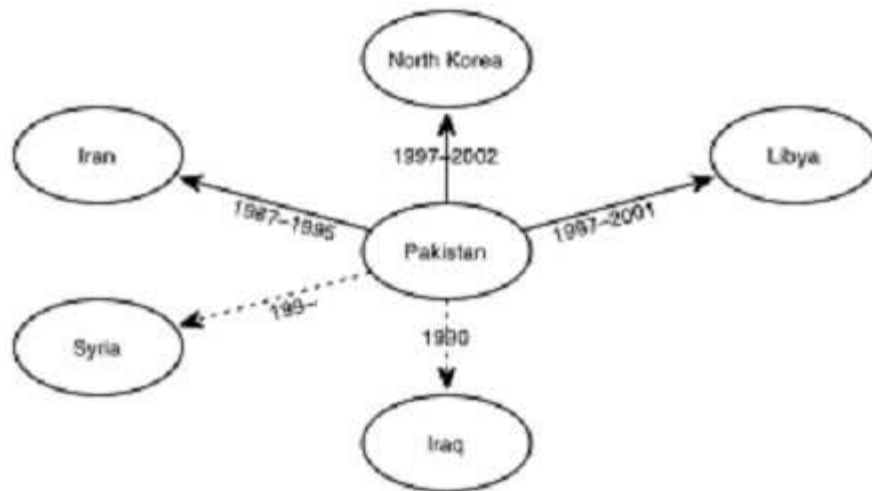


*Uncertain dates are marked as ~ (middle of decade), < (beginning of decade), or > (end of decade). Nodes are placed for clarity. Minor nodes are excluded.*

The second-tier missile proliferation network shown in [Figure 5](#) also exhibits a much more dynamic, network-like structure than the first-tier network. North Korea received early assistance from Egypt (1974-1981) and Iran (1988) before returning the favor by assisting both with their later developments of ballistic missiles. Libya and Syria assisted Iran early in its program, which was subsequently reciprocated. Some of these relationships represent single transactions (like the Iranian transfer of wrecked Iraqi missiles to North Korea in 1988), while others are more reciprocal and more stable.

Nuclear proliferation data from the A.Q. Khan network are pictured in [Figure 6](#). Pakistan is the hub, or central node, for this network. A.Q. Khan used the clandestine network to supply Pakistan's program, creating a clearinghouse for delivery of parts from private actors to Iran, Libya, and North Korea. It also offered parts to other countries, such as Iraq and possibly Syria.

**Figure 6: Network Structure of Second-Tier Nuclear Proliferation Rings.**



*Declined offers of assistance are dotted; uncertain dates are marked as ~ (mid-decade). Nodes are placed for clarity. Minor nodes are excluded.*

All four of the missile technology proliferators who received aid from both China and Russia (plus Libya, which may have also received assistance from both), were either approached by or received assistance from the A.Q. Khan network. In some ways, the network is an odd hybrid of transactions. Since the knowledge requirements for the production of nuclear weapons are higher than ballistic missiles, the number of suppliers is more limited, and transactions are more hierarchical. Knowledge requirements also restrict the ties that might otherwise be created due to structural pressures. Without access to the requisite knowledge, ties cannot be formed.

Missile technology thus appears to be more transferable than nuclear technology. Many of the relationships in [Figure 5](#) involve reciprocal exchanges. This, in part, may be due to the many small technical challenges posed by ballistic missiles that allow for more decentralization and specialization than nuclear weapons technology.[\[23\]](#) Because of the density of ties among the participating nodes, such networks are much more difficult to shut down.

## Conclusion

Why might nuclear proliferation networks initially look like stars, rather than rings or cliques, and how might they evolve? I argue that the tacit knowledge required to successfully build nuclear weapons results in nuclear proliferation networks that are more likely to adopt star structures. Missile networks are more likely to become cliques much faster. This constraint structures the proliferation networks. In a clique, only the central hub can dispatch experts to (attempt to) train new proliferators. But, the satellite states can help each other with acquiring equipment, but not tacit knowledge. While tacit knowledge always requires some trial-and-error experience, tutelage by someone who has already possesses the knowledge can speed up the process. A.Q. Khan delivered parts and plans to Libya, Iran, and North Korea, but nonetheless all of these countries have had difficulties producing nuclear materials. Indeed, this seems to have been North Korea's problem: "One official said that some information suggests the DPRK may have 'slavishly followed a recipe' calling for some more advanced components or materials, as called for in the design package provided by its helpers."[\[24\]](#) While Iran appears not to have followed the same route, the numerous problems it encountered in its program indicate that Pakistan was unable to transfer tacit knowledge easily.[\[25\]](#) This also seems to have been the case for Libya. These similar lags in time seem to indicate that they experienced the same tacit knowledge problems that other states have encountered. They bought "nuclear technology without actually knowing



how it worked.”<sup>[26]</sup> As a result, it appears that the damage done by A.Q. Khan’s network may be much less severe than initial reports implied.

Market incentives may restrict future nuclear proliferation networks. Hub states might have incentives to restrict information transfer. For example, they might sell parts for centrifuges, but not the instructions on how to create them in order to maintaining profits. Unfortunately, due to structural equivalence and transitivity, the individual satellite nodes are likely to form ties (nuclear or not) with each other due to their common connections with the hub, thus decreasing chance of a potential dismantlement of the network by eliminating the hub. Knowledge restrictions mean that missile transactions will tend more towards markets (like the first-tier missile proliferation network) and networks (like the second-tier missile proliferation network), while nuclear transactions will continue to be more hierarchical.

Since a star network can be shut down by eliminating the central node, it implies a policy of targeting the central node and discouraging satellite nodes from producing new connections by separating them. If “rogue states” are stopped from connecting with the rest of the world, they will be more likely to connect with each other—with potentially disastrous consequences.

While nuclear and missile proliferation networks contain very similar participants, the dynamics of these networks appear to be very different. Knowledge requirements seem to be a major reason for this difference, although they don’t entirely determine structure, at least in the case of missile proliferation. Transactions in the first-tier network were market-like; structural equivalence or homophily didn’t determine relations. Rather, strategic relationships and market pricing played a larger role, with two main suppliers selling technology to many different participants. These networks were star-shaped with central hubs; pressure exerted on Russia and China has thus been the best way to tackle these networks.

However, this market laid the groundwork for a more network-like structure in the second-tier proliferators, in which structurally equivalent actors from the first network formed ties and reciprocally developed missile programs. States that had connections to Russia and China over time formed an additional network which was more reciprocal and decentralized. Focusing on a small number of current or potential hubs may be the best way of stopping them. On the other hand, given the widespread diffusion of knowledge, efforts that address the entire network may be most efficient.

The nuclear network—in which knowledge played a larger role—incorporate a different set of actors than the missile network. Nuclear transactions have been more hierarchical, with a single supplier attempting a one-way transfer of knowledge. This network was star-shaped, similar to the first-tier missile proliferation networks. Stopping the hub of the nuclear network would seem to be the best policy. Efforts, therefore, should focus on bringing Pakistan into the nuclear supply regime and on minimizing the chances that North Korea or Iran could become new nuclear hubs. This may involve difficult tradeoffs, such as agreeing that these states can retain a civilian nuclear infrastructure in exchange for agreed limits on dissemination of the sensitive nuclear technologies involved with the front or back of the fuel cycle. While this may increase the threat that these countries will build and test nuclear weapons, stopping the spread of the knowledge required to create weapons is worth it.

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Alexander Montgomery is a joint International Security Program/Managing the Atom Project Research Fellow at the Belfer Center for Science and International Affairs in the Kennedy School of Government at Harvard University and a Political Science PhD candidate at Stanford University. For the 2005-6 academic year, he will be a postdoctoral fellow at the Center for International Security and Cooperation in the Stanford Institute for International Studies at

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